SCATTERING OF NUCLEONS BY NUCLEI AT HIGH ENERGIES

BY

SIGURD KÖHLER

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SIGURD KÖHLER
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The present dissertation is based on investigations published in the following papers.

I Polarization of nucleons by scattering with spin-orbit coupling. Arkiv för Fysik *8* (1954) 521.

II Polarization of high energy nucleons scattered by nuclei. Nuovo Cimento *2* (1955) 911.

III Polarization of high energy nucleons scattered by nuclei. Nuclear Physics *1* (1956) 433.

IV Approximate optical model expressions for the elastic scattering and polarization of fast protons by nuclei in the forward scattering peak. Nuclear Physics *6* (1958) 161.

V On the inelastic scattering of nucleons by nuclei at high energies. Nuclear Physics *9* (1958) 49.

Scattering of Nucleons by Nuclei at High Energies

Experiments with scattering of high-energy nucleons by nuclei have in the past proceeded along with the construction of high-energy accelerating machines. The analysis of the data at 90 MeV was successfully made by Fernbach, Serber and Taylor (1949), who, following an idea of Serber, showed that the total absorption and differential cross-sections could be well described by what has been called the optical model. They represented the nucleus, as felt by the scattered nucleon, by a sphere with a complex index of refraction, the imaginary part giving an absorption, i.e. transfer of nucleons to inelastic channels. Now it is, however, known that at negative energies in the ground state of a nucleus in the independent particle picture (shell model) a strong spin-orbit interaction is important, in addition to the central interaction of a nucleon moving in the field of the other nucleons. If this spin-orbit interaction persists even at higher energies, this will result in a strong polarization of nucleons scattered by nuclei. Oxley, Cartwright and Rouvina (1950) observed such polarizations at 240 MeV. E. Fermi (1954) was the first to show that the experiments did indeed agree with a spin-orbit interaction of the same strength as in the shell model, although the equality from the present state of the theory seems accidental. More importantly, he used a spin-orbit interaction with the radial dependence proportional to the gradient of the central one. Polarization measurements have since been made at several laboratories. Measurements of high precision have been made at the Gustav Werner Institute in Uppsala. At this institute and others it has also been possible to measure cross-sections and polarizations of protons scattered inelastically, transferring the scattering nucleus to a specific (low-lying) energy level.

In the above-mentioned phenomenological approach a number of constants—well-depths, potential forms and spin-orbit interaction strength—have to be determined from the experiments. However, important progress has been made during recent years in the solution of the many-body problem of high-energy scattering. This is in large part due to K. M. Watson. The optical model is here actually derived and the previously assumed gradient form of the spin-orbit interaction is confirmed. It is to be noted that an important idea is the same as that which led Serber to

apply the optical model and that is the concept of direct interaction, i.e. the nucleon is scattered by each single nucleon in the nucleus and the interactions that come into play are the same as in free nucleon–nucleon scattering. These are fundamental assumptions and can only be checked by comparison with experiments. Such comparisons have recently successfully been made by several authors after phase-shift analysis of nucleon–nucleon scattering had been made. The concept of optical model therefore now has a more fundamental basis.

The Schrödinger equation with the interaction Hamiltonian of a scattered nucleon represented by a spherical potential well is conveniently treated by a partial wave analysis. If a spin-orbit interaction is introduced into the Hamiltonian, neither the orbital angular momentum nor the spin of the scattered nucleon is a constant of the motion. The total angular momentum is, however, a constant. The formalism for scattering on a potential including spin-orbit interaction is presented in paper I. This paper includes expressions for polarizations and cross-sections for both neutron and proton scattering. A treatment of the spin-orbit interaction in Born approximation is also presented.

Papers II and III contain explicit calculations of cross-sections and polarizations, using a gradient spin-orbit interaction. We applied a semi-classical approximation, used by several authors, to obtain the necessary phase shifts. The validity of this approximation has later been investigated by Schiff and he found it reliable for small-angle scattering. We also included the Coulomb field in the calculations and it was found to give very important effects for the polarization. It was found that the applied interaction could describe the gross structure of the experiments fairly well. If one looks at the finer details of the curves, one notes, however, that the theory does not describe some characteristic features, especially for light nuclei like carbon and aluminium. As the calculations are approximate, one has, however, to ask if the deviations seen are due to an only approximate validity of the optical model or the approximate calculations. In spite of the approximation methods the computations were still very lengthy and required a lot of work for every set of parameters considered. However, the calculations on neutron polarization are very much facilitated if one more (small) approximation is made, i.e. if the spin-orbit interaction is treated as a perturbation. Then an explicit expression for the polarization is obtained, containing three parameters: the ratio of imaginary to real central well depths and a complex spin-orbit interaction constant. However, the real well depth, the form of the well or the nuclear size do not enter in. Exactly the same formula is obtained in Born approximation. We point out that although the derived expressions involve a consistent expansion of the scattering amplitude in the first order of the spin-orbit interaction constant, this does not lead to a consistent expansion for the cross-section (the squared amplitude), as then a second-order term from the spin-independent part of the amplitude has also to be included. This is done in paper I. This

second-order term has, however, roughly the same angular dependence as the zero-order term and is therefore negligible in comparison with this.

In papers II and III the spin-orbit coupling was treated as real. This simplified the calculations considerably, as just one parameter was left to vary to fit the polarization curves, as the shape of the well was fixed and the other parameters adjusted by fits to the cross-sections. The derivation of the optical model from nucleon-nucleon scattering data showed, however, that the spin-orbit coupling is a complex quantity. If one again treats this as a parameter, the amount of numerical work is increased considerably. In paper IV we therefore developed an approximation for the proton polarization, i.e. with inclusion of the Coulomb field (and the e.m. spin-orbit coupling) in the interaction Hamiltonian. These derivations enable one to cover a whole domain of parameter values with very little computational effort. They are especially useful for studying the effect of variations of the model parameters in the interesting, small-angle, Coulomb-nuclears cattering interference region. It is found that the detailed agreement with a light nucleus like carbon is not better after the introduction of an imaginary part of the spin-orbit coupling. These kinds of calculations are now performed exactly by high-speed computing machines and the approximate formulae are then of value for the discussions of these computations. They have also been used by Bethe and by others to test the optical model parameters derived from nucleon–nucleon scattering data.

Paper V is concerned with the inelastic scattering of a nucleon transferring the nucleus to a low excited state. Both the collective model and the direct nucleon–nucleon interaction aspect of the problem are considered. For the latter treatment a formalism for inelastic scattering is developed using the methods of Watson for quantum mechanical multiple scattering. The distortion of the scattered wave is treated in the above-mentioned classical approximation and the spin-orbit coupling is treated as a perturbation. The direct interaction model is restricted to the case for which the two-nucleon scattering matrix is reduced in the same way as it is for elastic scattering. Then the approximate but explicit expression earlier obtained for the elastic neutron polarization is again obtained for the inelastic polarization. The two models, collective and direct nucleon–nucleon, are found to give two slightly different results, and the second model agrees best with experiments. This is not taken as evidence that the second model is more correct. The first model, as treated here, is to be considered as an ansatz, while the second tries to start from fundamentals. We argue that the Coulomb field is unimportant for the inelastic scattering and one will thus also expect the proton polarization to be mainly independent of nuclear number. This result is so far in agreement with experiments.

A detailed test of the direct nucleon–nucleon interaction model still has to be carried out. The optical model for elastic scattering still has to be carefully tested

and corrections to it be sought. Especially the inelastic scattering should be a nice tool for the investigation of nuclear structure. The approximate methods presented in this dissertation are regarded mainly as a survey of the state of the theory. More exact treatments can be made using electronic computers.

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